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ENERGY
COMMISSION

Demonstration of a NOx Control System for Stationary Diesel Engines

PIER COLLABORATIVE REPORT

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Prepared By:
Electric Power Research Institute
B. Freeman, Principal Investigator
Palo Alto, CA 94304

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

John Beyer,
Contract Manager

Art Soinski,
Program Area Team Lead

MARTHA KREBS, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B.B. BLEVINS,
Executive Director

Demonstration of a NO_x Control System for Stationary Diesel Engines

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Co-sponsors

California Energy Commission
1516 Ninth Street, MS-29
Sacramento, CA 95814-5512

Project Manager
J. Beyer

Hawaiian Electric Company
P.O. Box 3978
Honolulu, HI 96812-3978

Project Manager
S. Seu

EPRI Project Manager
B. Freeman

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Catalytica Energy Systems, Inc.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

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CITATIONS

This report was prepared by:

Catalytica Energy Systems, Inc.
430 Ferguson Drive
Mountain View, CA 94043

Principal Investigator
S. Vilayanur

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

Principal Investigator
B. Freeman

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Demonstration of a Low NOx Control System for Stationary Diesel Engines, Commission Contract Number # 500-02-014 conducted by the Electric Power Research Institute. This project contributes to the Environmentally-Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

EXECUTIVE SUMMARY

Regulatory agencies are working throughout the U.S. to improve ambient air quality and reduce the public's exposure to airborne toxic substances. Because uncontrolled stationary diesel engines produce significant amounts of NOx and particulate matter, they are typically only permitted for limited run-time applications. California has over 26,000 stationary diesel engines, mostly in emergency power and direct drive applications. In the past few years, various incentive programs in the state have resulted in the change-out of older, dirtier engines for newer, cleaner models or replacement with electric motors. Emissions reductions can be accomplished by equipping existing engines with NOx and PM controls. The retrofit systems currently available, however, either are not cost competitive or are unable to provide the required emissions reductions.

The California Energy Commission, Hawaiian Electric Company, and the Electric Power Research Institute partnered to sponsor the development and demonstration of a proof-of-concept NOx control retrofit product. Catalytica Energy Systems, Inc. was identified as having unique technical capabilities and a novel design for a cost effective, regenerative, lean NOx trap system capable of >90% NOx reduction with properties favorable for the incorporation of a diesel particulate trap.

Catalytica's design features a single-leg, continuous, full-flow exhaust system with an inline fuel processor and lean NOx trap as shown in Figure ES-1. The key component of this system is the fuel processor, which produces reducing agents (H_2 and CO) that are used to regenerate the system's lean NOx trap. The fuel processor uses materials derived from Catalytica's Xonon Cool Combustion® product.

Under normal operation, exhaust gas exits the engine, passes through the Xonon fuel processor (XFP), and lean NOx trap (LNT) before exiting the stack. As the exhaust passes through the LNT, the NOx is adsorbed onto the LNT working surfaces, effectively removing it from the exhaust stream. Over time, the LNT becomes saturated with NOx and must be regenerated by converting the NOx to N_2. During a regeneration cycle, the emissions system control unit briefly throttles the engine to reduce the O_2 concentration in the exhaust gas from approximately 10% to approximately 6%. Simultaneously, a small amount of diesel fuel is introduced into the XPF where a portion of it is used to consume the remaining O_2 in the exhaust through a catalytically aided oxidation reaction. The balance of the diesel fuel is reformed in the XFP to produce H_2 and CO which react with the adsorbed NOx converting it to N_2 in the LNT. Under full-load operation, a seven second regeneration cycle is conducted once every 90 seconds.

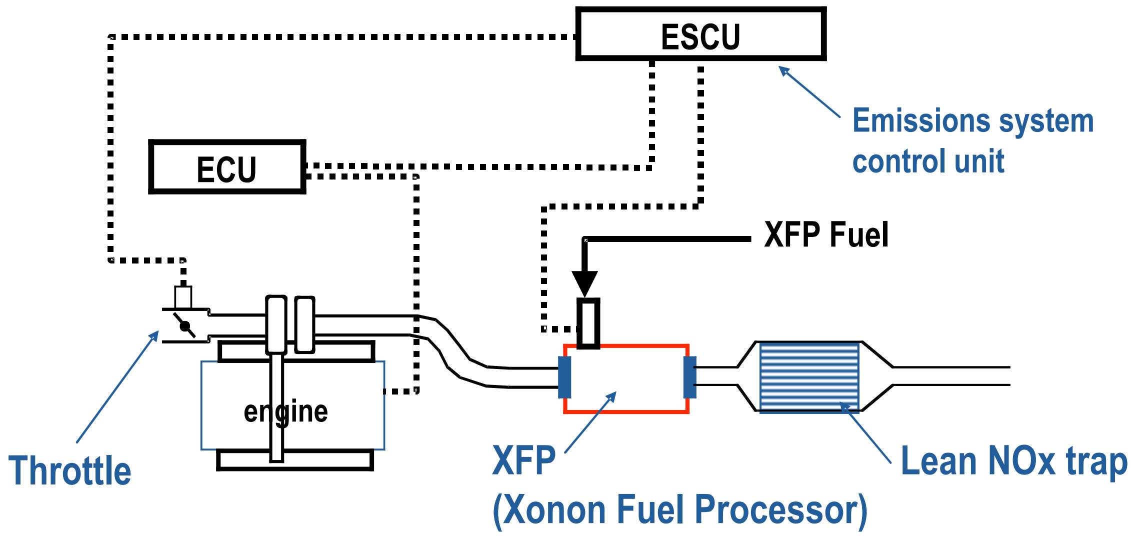

Figure ES-1
Catalytica's XEC-90 NOx Reduction System

Catalytica performed four major tasks in support of this project. In the first task, CESI retrofitted a diesel engine-generator with a throttle valve and automatic controls to verify the ability to periodically reduce O_2 in the exhaust stream to the 5-6% range. This was successfully achieved by partially closing the throttle for 2.0 seconds, opening it fully for 2.0 sec, and partially closing it again for 3.1 seconds. This resulted in a drop in exhaust O_2 concentration from 8.9% to approximately 6.0%. In the second task, Catalytica designed and fabricated a XEC-90 prototype system capable of functioning from idle to full load. Supporting activities include testing a sub-scale XFP under conditions that simulated full scale operation.

In the third major task, CESI identified and selected a NOx trap capable of meeting the performance requirements. Two types of trap were evaluated in sub-scale tests which measured NO_x reduction versus inlet gas temperature for new and steam-aged samples. Selection of the LNT was primarily based on the highest NOx reduction performance in the temperature range of interest. In the final major task, CESI installed a XEC-90 prototype system on a 8.3 liter diesel engine and operated it for 100 hours to validate the XFP and assess the NOx reduction performance. The cumulative NOx conversion averaged 92% over the 100-hour demonstration test as shown in Figure ES-2. During the test, the overall fuel penalty (increase over operation without the XEC-90 installed) was approximately 7%. It should be noted that this system was intended as a proof-of-concept system and was not optimized for minimum fuel penalty. During the 100-hour test, four desulfation cycles were performed to remove sulfur (originating in the fuel) from the LNT.

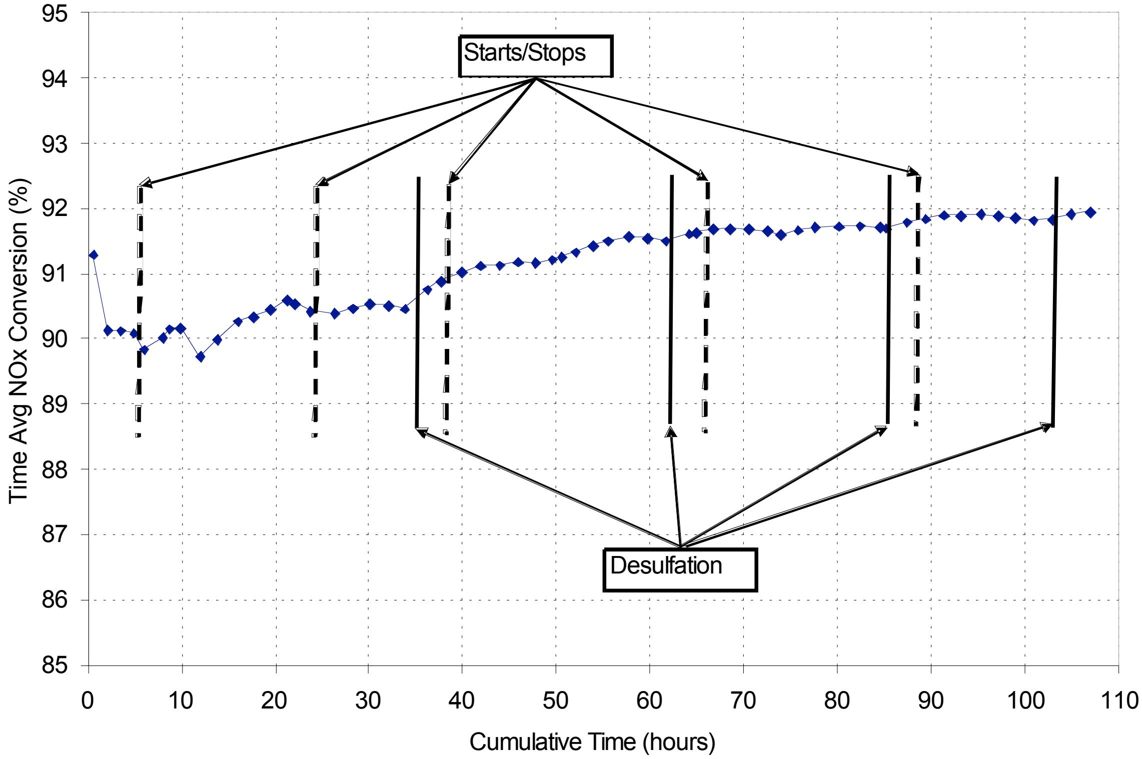

Figure ES-2
Cumulative NOx Reduction During 100 Hour Demonstration Test

Based on the performance results achieved from these Phase I activities, potential for continued performance improvements in Catalytica's XEC-90 design and projected market demand, continued product development and field trials as proposed in Phase II are recommended here. Under Phase II, Catalytica will integrate the XEC-90 with an ARB certified diesel particulate filter and produce two integrated units for field trials with a goal of 95% NOx and 85% diesel particulate matter removal with minimal fuel penalty.

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1
INTRODUCTION

Background

Diesel engines provide the people and industry of California with an invaluable service in mobile, power generation, and direct drive applications. In California alone there are over one million diesel engines in on- and off-road transportation applications, 50,000 units in portable applications, and 26,000 units in stationary applications. Despite their importance, current and pending regulations will significantly limit the future role of diesel engines in a cleaner California. Uncontrolled emissions from diesel engines are among the highest of any engine type, with NOx levels ranging from 6 to 12 g/bhp-hr (18 to 35 lb/MW-hr) and particulate matter (PM) emissions ranging from 0.4 to 0.5 g/bhp-hr (1.2 to 1.5 lb/MW-hr). Due to their detrimental effects on health and the environment, both NOx and PM are regulated on federal, state and local levels.

NOx is a byproduct of combustion that contributes to the formation of ground-level ozone. It also reacts with nitrate particles and acid aerosol to cause respiratory problems. NOx contributes to the formation of acid rain, which harms water sources, and it is a greenhouse gas. Because it can be transported by prevailing winds over long distances, NOx is controlled and regulated on a regional basis.

Diesel PM is defined, measured and controlled as diesel derived particulate matter less than 10 μm in size. It is a source of haze and scientific studies have linked breathing PM to significant health problems, including aggravated asthma, increases in respiratory symptoms like coughing and difficult or painful breathing, chronic bronchitis, and decreased lung function. In California, diesel PM has also been designated as a carcinogen.

Stationary Diesel Engines

The focus of this project and topic of this report is limited to stationary diesel engine emissions and emission control technologies. For the purposes of this report, stationary engines are defined as engines that operate in the same location for more than twelve consecutive months. In 2001, the California Air Resources Board estimated there were 26,000 stationary diesel engines in California comprised of 19,659 emergency back-up generators (also known to as BUGs)[1], 5,338 agricultural pump engines, and 1,319 in miscellaneous direct drive engine applications, including

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[1] *Initial Statement of Reasons for Proposed Rulemaking: Adoption of the Proposed Airborne Toxic Control Measure for Stationary Compression-Ignition Engines; Stationary Source Division, Emissions Assessment Branch, Sacramento*, September 2003, CARB 2003 Staff Report

industrial process, prime power, rock crushing, crane operation, etc. A more recent CARB audit of stationary agricultural engines found that an estimated 5,900 diesel-fueled engines were serving in stationary agricultural pump applications[2]. Adjusting the 2001 data to account for the increase in agricultural pumping engines, Figure 1-1 shows the estimated number of stationary diesel engines in California.

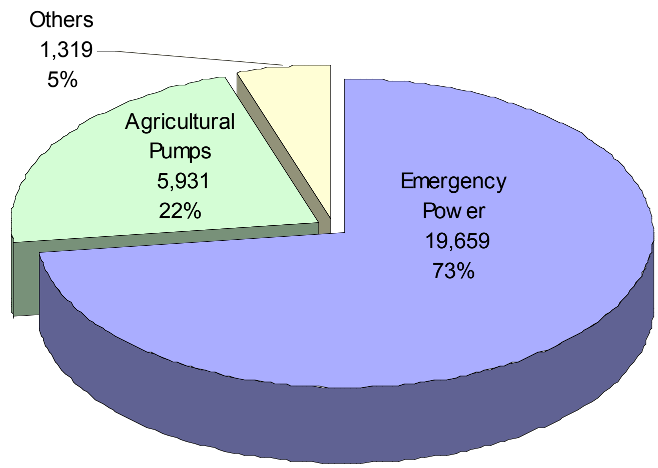


Figure 1-1
California Stationary Diesel Engines as Identified by ARB

Agricultural Pumping Applications

Stationary diesel engines in agricultural applications are primarily used for well and irrigation pumping. They have enjoyed protection under the federal Clean Air Act of 1990, which exempts them and other farm equipment from emission regulations. As a result, agricultural engines are typically older models with higher exhaust emissions. Collectively, agricultural engines contribute significantly to overall pollution in agriculture regions due a combination of high usage and high emissions. In 2003, ARB estimated that emissions from these engines accounted for 23% of the NOx and 17% of the particulate matter in the Central Valley. Since 1998, a concerted effort has been made to provide incentives to farm owners to exchange older uncontrolled engines with newer, cleaner models through the Carl Moyer Program (described below). Since the Program's inception, more than 2,200 older diesel engines have been replaced with newer engine models or with electric motors. The environmental benefit to the state is calculated to be emissions reductions of 1,910 tons/year of NOx and 92 tons/year of PM[3]. An alternative to engine replacement or electrification is an emission control retrofit for existing engines.

[2] *Updated Statewide Population and Emission Inventory for Diesel-Fueled Agricultural Irrigation Pumps (memorandum)*. April 30, 2003. California Air Resources Board
[3] *Carl Moyer Program Annual Status Report*. February 2004. California Air Resources Board.

Demand Response and Peaking Power Production Applications

In this role, an engine generator is run to provide all or part of an end-user's electrical load, generally during periods when the price of utility power exceeds the cost to produce power from the generator. Owners may dispatch their generators during high system demand periods when given a signal from the utility in return for payment or billing credit. This practice is known as "demand response." Alternatively, generator owners may dispatch their generators during hours when fuel and maintenance costs are lower than utility kWh rates (typically mid-day to late afternoon) or to limit monthly billing demand. This practice is known as "peak shaving."

Existing diesel-fueled emergency generators are naturally suited for these roles because they are already installed, connected to critical loads, and often paid for. However, BUGs are not normally allowed to operate in a peak-shaving mode under their emergency generator permit. In order to do so, they must be re-permitted as a power generator. However, because of their high emissions, uncontrolled diesel BUGS cannot generally acquire a power generation permit in California. If highly effective emission controls were added to an emergency generator, it would be possible to re-permit the unit and use it for peak-shaving or demand response while remaining under local NOx emission levels for new diesel BUGs. Table 1-1 summarizes the Best Available Control Technology (BACT) trigger levels for stationary diesels for each of California's air districts.

Table 1-1
BACT Trigger Levels for Stationary Diesels in California

California Local Districts	BACT NOx Trigger
Kern Co.	any increase
Antelope Valley, South Coast	1 lb/day
San Joaquin Valley	2 lbs/day
Bay Area, El Dorado Co., Placer Co., Sacramento Metro, San Diego Co.	10 lbs/day
Mojave Desert	15 lbs/day
Colusa Co., Feather River, Glenn Co., Imperial Co., Monterey Bay U., San Luis Obispo, Santa Barbara, Shasta Co., Tehama Co.	25 lbs/day
Butte Co.	50 lbs/day
Lake Co., Lassen Co.	150 lbs/day
Great Basin U., Modoc Co., Siskiyou Co.	250 lbs/day
Mendocino Co., North Coast U., Northern Sonoma	40 tons/yr
Northern Sierra	100 tons/yr

As an example, Table 1-2 shows the potential for increased operation of a 500 kW (670 hp) uncontrolled diesel engine that normally produces 8 g/bhp-hr (23 lb/MW-hr) of NOx emissions, operating in Sacramento. If this unit were used in a peak-shaving application during the 122-day peak season (June 1 to September 30)[4] the engine would reach the BACT limit in less than an hour. Having a 90% NOx reduction system would allow the engine to operate for up to 8.5 hours before reaching the BACT trigger of 10 lbs NOx/day (see Table 1-2). The table also shows the amount of NOx this engine would offset compared to the same engine equipped with emission controls if the two engines were operated for the same amount of time.

Table 1-2
Estimated Useful Operating Hours Before Trigging BACT (10 lb NOx per day)

	Time and NOx Limits before BACT Triggered			
	Daily		122 Day Period	
BUG Application in Sacramento	**Hourly NOx (lb)**	**Daily Max (hours)**	**Max (hours)**	**ΔNOx (tons)**
Uncontrolled 500 kW Engine (@ 8 g/hp-hr NOx)	11.8	0.85 (51 min.)	102	0.62 datum
With 90% Reduction (0.8 g/hp-hr)	1.2	8.5	1,037	6.1
With 95% Reduction (0.4 g/hp-hr)	0.6	16.9	2,062	12.2

A growing number of electric utilities are establishing programs to aggregate and dispatch their customers' BUGs during times when power resources are very limited so as to avoid critical power situations or even blackouts. EPRI identified ten such programs representing 223 engines and 133 MW of capacity in the U.S., including the San Diego Gas & Electric (SDG&E) Rolling Blackout Reduction Program (RBRP)[5]. Advancements in remote communication and control technologies help facilitate this practice, but it is still limited by the lack of economic retrofit emission reduction systems that are necessary to re-permit the diesel BUGs as power generators.

Regulatory Drivers for Clean Engines

The California Air Resources Board (ARB) promulgates an emissions Guidance, but each district office is responsible for setting and controlling NOx and PM levels in their respective region through regulated and permitted operation of engines and other devices. In the past few years, new rules and regulations have emerged which will act to lower the amount of pollutants that diesel engines are allowed to emit. By design, these rules have significant potential and

[4] Sacramento Municipal Utility District: electric rate schedule GS-TOU2
[5] *Utility Dispatch of Customer-sited Distributed Energy Assets*. December 2004. Primen (a subsidiary of the Electric Power Research Institute)

means to change how, where, and for how long diesel engines can operate. Thus far, the market response has been to replace the engines with electric motor drives and to exchange older engines for newer, cleaner engines. There remains a market gap for economic retrofit systems.

Air Toxic Control Measure

In August 1998, following a ten-year investigation, ARB classified diesel PM as a toxic air contaminant (TAC) based on its ability to cause cancer. The statewide average cancer cases caused by diesel PM was estimated to be 500 per million from a statewide population weighted ambient concentration of 3.2 $\mu g/m^3$. In 1998 and 1999, the South Coast Air Quality Management District (SCAQMD) conducted a study that found diesel PM accounted for 71.2% of the total ambient air toxic risk to southern California residents, ranking higher than other known and suspected airborne carcinogens, including 1,3-butadiene (9.8%), benzene (7.5%), carbon tetrachloride (4.0%), among others[6].

This finding led ARB to develop new rules to reduce diesel PM from all engine applications. In September 2000, ARB approved the Diesel Risk Reduction Plan with the goal of reducing diesel PM emissions and the associated potential cancer risks by 75% in 2010 and by 85% or more in 2020. ARB estimates that California's diesel engines collectively produce 28,000 tons of PM annually. The impact this will have on stationary diesels is shown in Table 1-3.

Carl Moyer Fund

In 1999, ARB passed the Carl Moyer Memorial Air Quality Standards Attainment Program (Moyer fund), which provides rebates on an incentive basis for the incremental cost of cleaner-than-required engines and equipment. Eligible projects include on-road, off-road, marine, locomotive, and stationary agricultural pump engines, as well as forklifts, airport ground support equipment, and auxiliary power units. The program achieves near-term reductions in emissions of NOx, which is necessary for California to meet its clean air commitments under the State Implementation Plan (SIP) established in 1994.

Funding for the Moyer fund was increased with the passage of Proposition 40, the California Clean Water, Clean Air, Safe Neighborhood Parks, and Coastal Protection Act, in 2002. The scope of the Carl Moyer incentive program was broadened under AB 923 which added PM controls for agricultural engines. In the first three years of operation, the Carl Moyer fund reduced NOx by an estimated 4,123 tons/yr at a cost of $4,006/ton.

The amount of incentive payments is determined by the quantity of NOx offset with a new engine compared to the levels from existing equipment. The Moyer Fund has a cap of $13,600/ton of NOx reduction, however, actual awards have averaged less than $3,000/ton.

[6] *Multiple Air Toxics Exposure Study (MATES-II): Final Report,* March 2000. South Coast Air Quality Management District

Table 1-3
PM Emission Limits Under ARB's ATCM Rules

	Diesel PM Limit (g/bhp-hr)				
	unlimited operation	**<20 hrs/yr**	**21-30 hrs/yr**	**31-50 hrs/yr**	**51-100 hrs/yr**
*Engines installed & permitted **after** 1-1-05*					
Emergency Generator, during emergency	0.15*	0.15*	0.15*	0.15*	0.15*
Emergency Generator, non-emergency		0.15*	0.15*	0.15*	0.01*†
Prime Power	0.01*	0.01*	0.01*	0.01*	0.01*
Agricultural	0.15*	0.15*	0.15*	0.15*	0.15*
*Engines installed & permitted **before** 1-1-05*					
Emergency Generator, during emergency	N.A.	N.A.	N.A.	N.A.	N.A.
Emergency Generator, non-emergency		N.A.	0.40	0.15†	0.01†
Prime Power	0.01•	0.01•	0.01•	0.01•	0.01•
Agricultural	N.A.	N.A.	N.A.	N.A.	N.A.

* or, Off-Road Engine Certification Standard for an off-road engine of the same horsepower rating; whichever is *more* stringent
† with District Approval
• or reduce PM by 85%; or reduce PM 30% by Jan 1, 2006, and meet 0.01 by 2010

SB 700 (Florez)

This bill eliminates the permit exemption for agricultural sources of air pollution. It requires districts to permit agricultural sources that exceed 50% of the major source threshold, unless the district finds that permits are not necessary and that they would be disproportionately burdensome. SB 700 effectively closes the permitting exemption that agricultural engines have enjoyed under the Clean Air Act of 1990.

Utility Incentives for Agricultural Electrification

On June 16, 2005, the Public Utilities Commission (PUC) approved applications submitted by Pacific Gas & Electric (PG&E) and Southern California Edison (SCE) to offer a reduction in electric rates and line extension allowances for their agricultural customers who exchange diesel engine driven pumps for direct drive electric motor pumps. The incentive offers PG&E customers a 20% discount and SCE customers a 12.5% discount to otherwise applicable rates for a period of ten years, with a 1.5% annual escalation rate. The PUC received public comment on the applications prior to approval. Concern was voiced about the potential negative impact this new electrical load – estimated at 400 MW at peak times – would have on the state's electricity reliability during peak demand. For reference, California's Independent System Operator (CAISO) assessed Southern California's 2005 summer peak to be just 409 MW[7] less than available supply for a 1-in-2-year event.

SB 1298 Distributed Generation Clean as Central Station

On November 15, 2001, ARB adopted a regulation that established a distributed generation (DG) certification program as required by Senate Bill 1298[8] (chaptered September 2000). The DG certification program requires electrical generation technologies that are exempt from district permit requirements (see Table 1-4) to be certified by ARB to specific emission standards before they can be sold in California.

Table 1-4
ARB's Proposed 2007 DER Emission Limits

	NOx		VOC		CO	
	lbs/MWh	g/bhp-hr	lbs/MWh	g/bhp-hr	lbs/MWh	g/bhp-hr
2003 without CHP	0.5	0.17	1.0	0.34	6.0	2.04
2003 with CHP	0.7	0.24	1.0	0.34	6.0	2.04
2007	0.07	0.02	0.02	0.01	0.1	0.03

Emission Control Technologies

NOx Control

There are two modes for controlling NOx emissions. The first is to control and limit the formation of NOx during the combustion process. The second is to reduce NOx after it is produced. Both modes are effective in moderately reducing NOx and the two can be used in tandem to achieve higher removal efficiencies.

Combustion control measures include retarding the timing – common on most commercial engines – and exhaust gas recirculation (EGR), an emerging technology. These measures can reduce NOx on the order of 50%.

Common exhaust after-treatments include selective catalytic reduction (SCR) which is in widespread use, particularly in Europe. SCR is up to 90% effective, but is costly, requires a large

[7] *2005 Summer Operations Assessment*, March 23, 2005. California ISO.
[8] http://www.arb.ca.gov/energy/dg/sb1298bill20000927chaptered.htm

footprint, and presents the hazards of on-site ammonia or urea storage and ammonia slip. NOx catalysts and lean NOx traps are the most promising technologies capable of >90% NOx removal. These are an emerging technology option for diesel engines.

Diesel PM Control

Catalyzed diesel particulate traps (DPT) are the best available technology for significant reduction of particulate matter. They are effective in reducing 85-90% of diesel particulate matter and are commercially available. As with other catalysts, DPTs are sensitive to sulfur and their effectiveness decreases in the presence of high sulfur loading in exhaust gas.

Recognizing the benefits of DPTs and the negative impact sulfur has on them, ARB passed a rule which requires that, effective January 1, 2006, diesel fuel produced for California must contain no more than 15 ppmw sulfur[9]. Allowing nine months of lead time between production and distribution, the rule further stipulates that after September 1, 2006, all diesel fuel sold at retail facilities must contain no more than 15 ppmw sulfur.

Market Need for Diesel Retrofit Options

The confluence of regulations requiring cleaner diesel engines (SB 700, ACTM, SB 1298) with incentive programs to promote engine switching (PG&E and SCE electric rates, Moyer Fund) has created a need for NOx and PM retrofits for existing diesel engines. In some instances, whole engine replacement or electrification will be the lowest cost option. However, widespread electrification may cause unwanted strain on the California energy supply during the peak power season.

In response to this need, the Electric Power Research Institute (EPRI), the California Energy Commission (Energy Commission), and Hawaiian Electric Company (HECO), partnered to further the development of an emerging emission control technology for retrofitting stationary diesel engines. The system would need to reduce NOx and PM with a minimum fuel penalty, incorporate a control system for automatic operation, and be cost competitive. EPRI found no such systems in, or preparing to enter, the market.

This project also fits the mission and goal of the Energy Commission's Environmentally Preferred Advanced Generation (EPAG) unit of the Public Interest Energy Research (PIER) program, which has the objective of:

> Facilitating widespread use of non-renewable distributed generation (DG) and improving California's air quality by developing reliable, inexpensive, emission-reduction technologies for reciprocating engines, small turbines and microturbines, fuel cells, and hybrid fuel cell-microturbine technologies... In the near-term, this means reducing the emissions of reciprocating engines and standardizing interconnection requirements[10]…

[9] Amend section 2281, title 13 of California Code of Regulations (www.arb.ca.gov/regact/ulsd2003/ulsd2003.htm)
[10] http://www.energy.ca.gov/pier/epag/index.html

Catalytica Energy Systems, Inc. (CESI or Catalytica) was identified as having unique technical capabilities and a novel design for a cost effective, regenerative lean NOx trap system capable of >90% NOx reduction and an integrated diesel particulate trap. CESI was retained to develop and demonstrate a full-scale proof-of-concept prototype.

Technology Description

At the core of Catalytica's system is a Xonon Fuel Processor (XFP) with a third-party, commercial lean NOx adsorber trap that will achieve >90% NOx reduction. The XFP converts diesel fuel to reactive reductants such as H_2 and CO to rapidly and completely regenerate the NOx trap. (A detailed discussion of the XEC-90 technical approach is discussed in Section 2.) NOx trap systems have been developed for heavy duty diesel vehicles and CESI has demonstrated that the combination of its XFP with a NO_x trap on 5.0 and 7.2 liter engines can achieve >90% NOx reduction.

The XEC-90 combines the following components adapted to an existing diesel engine generator set:

- Throttle valve system
- XFP inline with the exhaust
- NOx adsorber (NOx trap) from a third party supplier
- Controller (Emissions System Control Unit [ESCU]) that will take engine rpm and load data from the engine and control the above components to achieve the required level of NOx control.

The XEC-90 system uses a NOx trap installed in the exhaust system to trap the NOx. The NOx trap is periodically regenerated with H_2 and CO produced from diesel fuel in the XFP. These reductants convert the trapped NOx to N_2. Modifications to the engine include addition of a throttle system to provide the desired oxygen control during the regeneration cycle. The 8.3 liter, 160 kW, Cummins stationary generator set at CESI's Mountain View facility provided an ideal demonstration engine since this facility has full instrumentation and exhaust emissions measurement capability.

Project Objectives

CESI's XEC-90 Development Program is planned in three phases: Technology Demonstration (Phase I), Field Demonstration (Phase II), and Pilot Production (Phase III). The goal of Phase I, the topic of this report, is to demonstrate a NOx reduction technology on a 160 kW diesel-fueled reciprocating engine that can be scaled up to a size range of 250 to 2,000 kW in Phase II. The measurable objective is to achieve 90% NOx removal using Catalytica's XEC-90 technology for 100 hours of base-load operation and to measure the fuel penalty associated with achieving the 90% NOx reduction. The Phase I Technology Demonstration activities were completed in December 2004 with full-scale engine testing at CESI's R&D facility in Mountain View, California.

In Phase II, an ARB-verified, regenerative diesel particulate trap will be integrated into the XEC-90 system design and two units will be developed and installed on two diesel engines for field demonstration testing, with a goal of achieving 95% NOx reduction. Phase III consists of pre-commercial, limited release operation at multiple commercial sites.

Report Organization

This report is organized in four Sections. This, the first section, provides an introduction and explanation of the XEC-90 technology, regulatory forces acting on the market, and a framework for the testing work described in this report. The second section describes the four major tasks that CESI undertook in performing this work and the methodology used to derive the testing plan. Section three explains the outcomes from each of the four tasks and the significance of these outcomes. System schematics, data tables and charts illustrate how the XEC-90 performed during the 100-hour test with a full-scale diesel engine. Section four describes the conclusions from Phase I and makes specific recommendations for Program Phases II and III.

2
PROJECT APPROACH

System Approach

The Phase I XEC-90 prototype system consists of an Emissions System Control Unit (ESCU), a throttle valve, the Xonon Fuel Processor (XFP) and lean NOx trap (LNT) integrated with a 8.3 L diesel engine generator rated for 160-kW of continuous duty (see Figure 2-1).

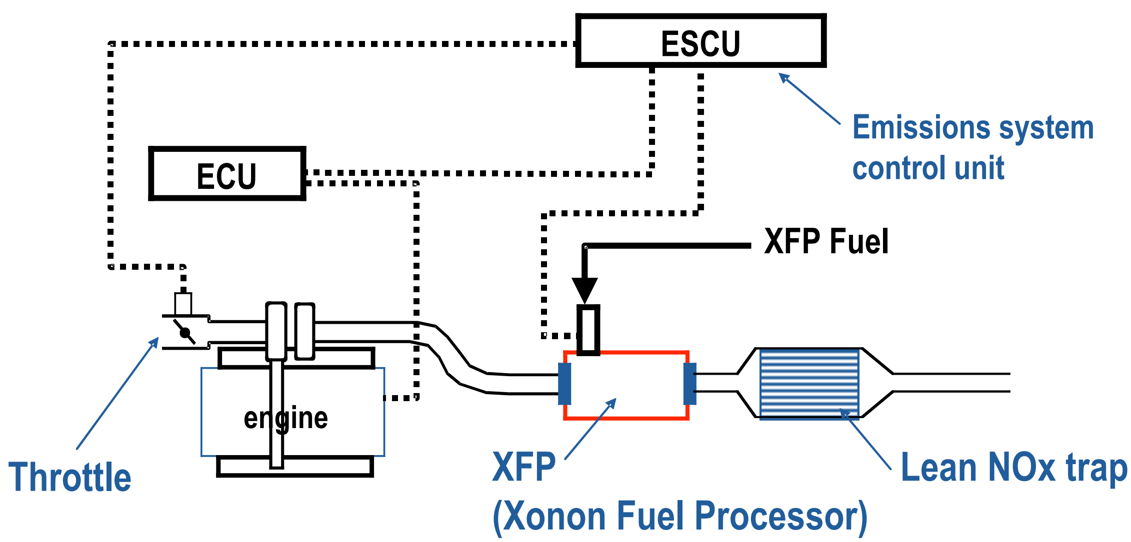


Figure 2-1
Full-scale Test System

Under normal base-load operation, the engine exhaust contains 9% O_2 and 700 ppm NOx in lean conditions. The exhaust passes through the LNT where NOx is adsorbed and periodically oxidized to NO_2 as described by the following chemical reactions. Note that M denotes the base metal that is proprietary to the NOx adsorber suppliers.

Lean Adsorption $2NO + 1.5O_2 + MO \square\ M(NO_3)_2$

Lean Oxidation: $2NO + O_2 \square\ 2NO_2$

To regenerate the LNT, the ESCU throttles the engine by closing the throttle valve added to the engine's air intake. Throttling reduces the oxygen in the exhaust from 9% to ~6%. Diesel fuel is then injected into the XFP where ~50% of the injected fuel is oxidized to consume the remaining oxygen, creating heat and an oxygen-free, fuel rich reducing condition. The remaining fuel is endothermically reformed into hydrogen (H_2) and carbon monoxide (CO) as represented by the following chemical reactions.

Fuel Oxidation: Diesel + O_2 $\square$ $H_2O + CO_2$

Fuel Reformation: Diesel + H_2O $\square$ $H_2 + CO$

Under these rich reducing conditions the nitrates stored on the NOx adsorber decompose and react with the H_2 and CO to yield N_2, as shown in the following chemical reactions.

Rich Desorption: $M(NO_3)_2$ + [H_2 or CO] $\square$ MO + NO_2

Rich Reduction: NO_2 + [H_2 or CO] $\square$ N_2 + [H_2O or CO_2]

The key advantage to the XEC-90 system over competing technologies is the method of regenerating the NOx trap, which results in low installed cost, low operating fuel penalty and a simple single-leg system.

Competing systems use alternative regenerating approaches, such as direct diesel injection and off-line reformers. The direct diesel injection method has a limited operating temperature range, seldom provides complete NOx trap regeneration, and significantly increases fuel penalty to achieve 90% NOx reduction. Off-line reformers operate continuously. To reduce fuel penalty they can utilize only a fraction of the engine exhaust flow to regenerate the NOx trap. An off-line reformer requires a complex dual-leg NOx trap approach where one NOx trap leg is under lean oxidation/adsorption conditions while the second leg is under rich desorption/reduction conditions.

Diesel exhaust contains sulfur, primarily as sulfur dioxide, derived from diesel fuel and engine lubricating oil. In the presence of an oxidation catalyst, these compounds form stable sulfates with the NOx storage materials of the NOx trap. The desorption of sulfur is more difficult than the desorption of NOx, so sulfates tend to accumulate on the NOx trap. As this happens, NOx trapping performance gradually decreases as fewer sites are available for NOx adsorption.

In general, the sulfur poisoning is reversible. A desulfation process involving decomposition of the sulfate species can restore the NOx adsorption site activity. The desulfation of NOx traps requires temperatures between 600 and 750°C (depending on NOx trap chemical composition) under reducing conditions accompanied by exposure to reductants such as H_2 and CO.

In theory, the desulfation of NOx traps can restore their full adsorption capacity. In practice, a permanent performance loss after repeated desulfation results from thermal degradation of washcoat and catalyst materials exposed to high temperatures during the desulfation process. Excessively frequent desulfation may involve significant fuel penalties and accelerated thermal deterioration of the catalyst. Therefore, to maintain a reasonable fuel penalty and slow the thermal deterioration from desulfation, the XEC-90 requires Ultra Low Sulfur Diesel (ULSD) fuel containing less than 15 ppmw sulfur.

The XFP in the XEC-90 allows for a carefully controlled desulfation process. The XFP raises the NOx trap temperature to the desired desulfation temperature in a controlled manner. As the NOx trap temperature is raised, H_2 and CO are generated by the XFP to liberate the sulfur.

Project Description

CESI undertook four major technical tasks to accomplish the project objectives. In the first major task, CESI retrofitted their Mountain View Diesel Generator Set with the necessary equipment to automatically control the regeneration cycle. The retrofit effort included the installation and characterization of a remotely modulated throttle valve located on the engine air intake. CESI also modified an existing LabVIEW control program to automatically coordinate the throttle valve operation with the fuel injection to the XFP. The control program was made flexible to allow for different inputs to trigger a regeneration or desulfation cycle. The flexibility allowed CESI to evaluate a simple time-based regeneration cycle versus a measured NOx concentration approach. The data collected allowed CESI to weigh control system simplicity against NOx reduction and desulfation performance. The key deliverable was the results of control system testing that demonstrated automated throttle control.

In the second major task, CESI designed and fabricated an XEC-90 prototype system capable of functioning from idle to full load. Design considerations were made for each of the key sub-components: head-end, XFP, thermal mass, and LNT. The resulting XEC-90 hardware is shown in Figure 3-2. The engine exhaust enters the XEC-90 through the head-end. The head-end was designed for aerodynamically uniform flow of exhaust and injected fuel into the XFP. The XFP section was sized to have sufficient reforming activity, moderate pressure drop, and reasonable fuel penalty under full load conditions (~12,000 standard liters per minute[slpm]). The thermal mass was sized to absorb a majority of the heat generated during XFP operation and prevent the NOx adsorbers from overheating. The frontal area of the NOx adsorbers was sized to maintain a reasonable pressure drop. An aerodynamic transition between the thermal mass and NOx adsorbers was designed to minimize flow separation and back-mixing, which would lead to ineffective use of the reductants generated by the XFP. The hardware design included attributes such as flanged sections and multiple access/instrumentation ports to maximize flexibility.

Supporting activities included the validation of a sub-scale XFP under the appropriate operating conditions prior to engine testing. Standard tests were used to measure the XFP light-off and reforming activities. For reforming tests, the operating conditions included low temperature, high fuel/air ratio test points that stressed the kinetic activity of the catalyst. The key deliverables were drawings of the XEC-90 prototype hardware.

In the third major task, CESI identified and selected a NOx trap capable of meeting the performance requirements. This task included contacting the major NOx trap vendors, evaluating their interest in the stationary diesel market, and conducting sub-scale tests on NOx trap samples supplied by interested vendors. CESI was able to complete negotiations with only two NOx trap vendors to support the program schedule, so only two types of trap were evaluated. Sub-scale evaluation of the traps involved measuring NOx reduction versus inlet gas temperature for fresh (as received from the vendor) and steam-aged samples. Testing on a sub-scale LNP determined the target desulfation temperature. Selection of one of the two NOx traps was primarily based on the highest NOx reduction performance in the temperature range of interest. The key deliverable was the conclusions from an internal design review that supported the NOx trap selection.

In the final major task, CESI installed the XEC-90 prototype system on their Cummins 8.3 liter engine and operated it for 100 hours to assess NOx reduction. This task included the development of the test plan to shake-down the system hardware/software, the throttling and fueling schedules to regenerate and desulfate the NOx trap, and the operational strategy and guidelines to achieve the 100 hours of demonstration testing. CESI's test plans detail the hardware build configuration, the location of instrumentation, the catalyst production/serial number, and each step of the test so that the test engineers that executed the plan would have clear instructions. The key deliverables were the test plan and summary results of the 100-hour demonstration test.

3

PROJECT OUTCOMES

Task 1: Retrofit Test Engine

Catalytica retrofitted the Cummins 8.3 liter, 160 kW, generator set (model DGFB) with a throttle valve and control system to enable automatic control of the fuel/air mixture. Figure 3-1 shows the change in the oxygen concentration (as measured by a NOx/O_2 sensor) in the exhaust stream over two throttling cycles of the automatic throttle valve. The automated control was set to briefly throttle the O_2 concentration to the 5-6% range. In this plot, the throttle schedule is partially closed (68% open) for 2.0 seconds, released (100% open) for 2.0 sec, partially closed (68% open) for 3.1 seconds and released. The cycle is repeated every 90 seconds. The drop in O_2 value from 8.9% to approximately 6.0% during throttling confirms the throttle operation and the repeated cycle confirms operation of the automated sequence.

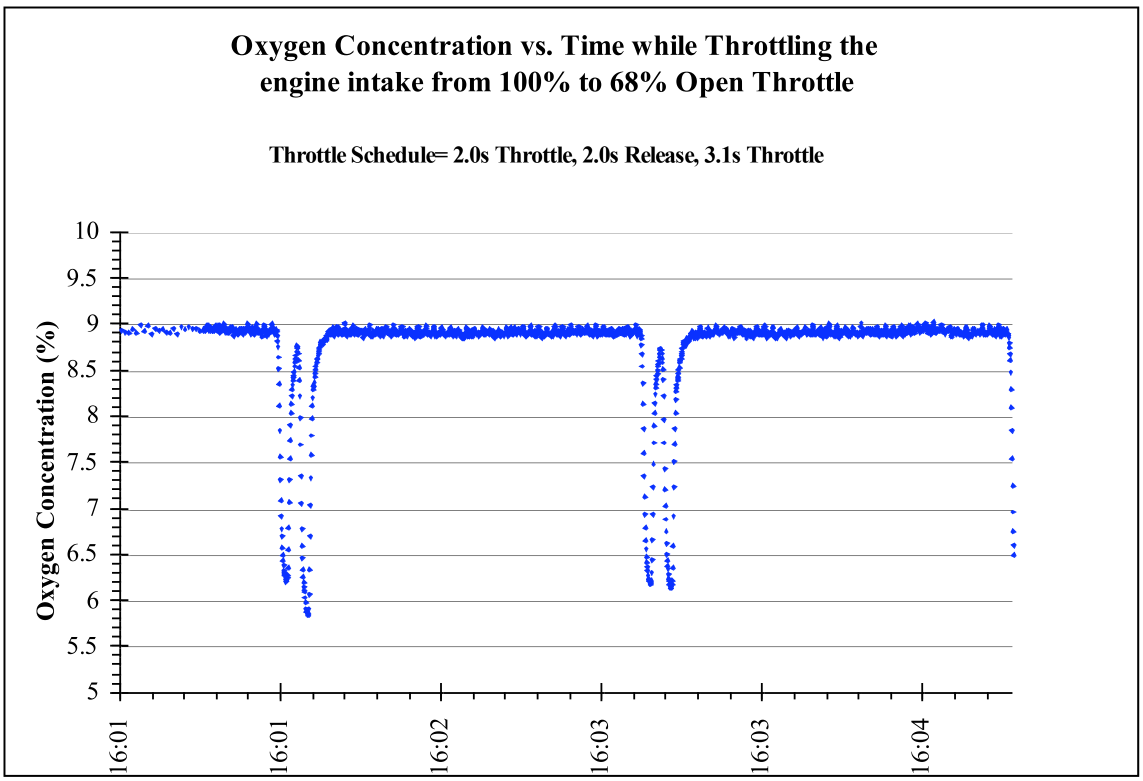


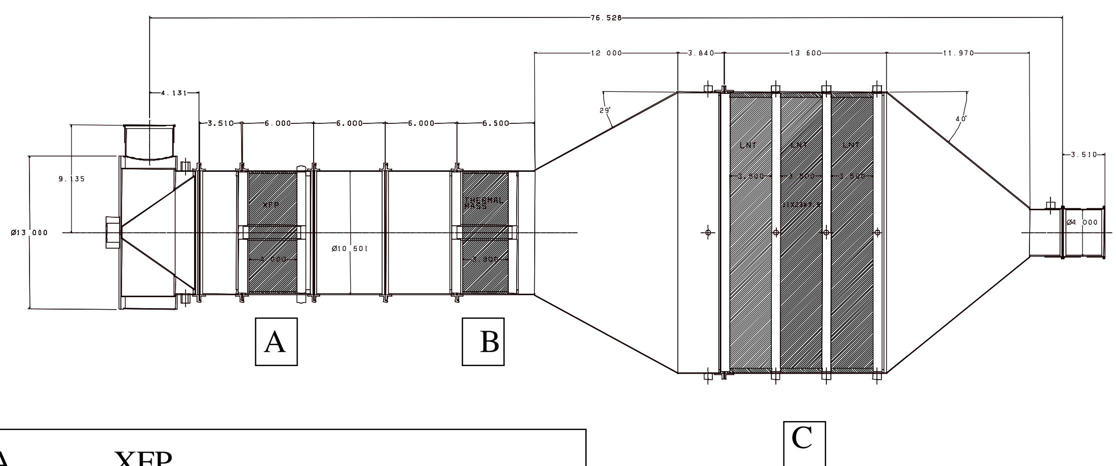
Figure 3-1
Demonstration of Automated Throttle Control

Conclusions: After calibration, the inline NOx/O_2 sensor provided an accurate measurement of the exhaust composition and the fuel flow meter provided an accurate measurement of engine fuel consumption. The upgraded LabVIEW control system performed the automated throttling, as designed, to reduce the O_2 concentration to the 5-6% level for the regeneration cycle.

Task 2: Build Demonstration Unit

Catalytica characterized their fuel processor and produced a full-scale XEC-90 demonstration unit. Portions of Task 2 work were funded directly by Catalytica; due to the confidential nature of proprietary design elements, the details are not described in this document. Sub-scale testing of several XFP formulations was performed to measure catalyst light-off temperature and reforming activity. The performance data were combined with numerical model calculations of the XEC-90 base load operating conditions (700 ppm NOx, 12,000 slpm exhaust flow, 500°C exhaust gas temperature, 10% O_2 unthrottled and 6% O_2 throttled) to size the XFP and estimate fueling schedules for the full scale unit.

A full scale XEC-90 test unit was designed based on the performance of sub-scale testing and two full scale XFP modules were manufactured (primary and back-up). A cross-sectional layout drawing of the XEC-90 hardware is shown in Figure 3-2. A sample of the full-scale XFP catalyst material was validated in CESI's 2-inch sub-scale fuel processor rig to ensure the XFP light-off and reforming activity were within specification.



A	XFP
B	Thermal Mass
C	NOx Traps

Figure 3-2
Cross-section of XEC-90 Prototype Hardware

Results/Conclusions: The XEC-90 hardware was designed and fabricated. The XFP catalyst materials were evaluated and down-selected.

Task 3: NOx Trap Technology Evaluation

In this Task, Catalytica evaluated several NOx traps for their suitability in the XEC-90 system. The specifications and performance of available NOx traps that met design requirements were evaluated and ultimately two candidate traps were selected from two different vendors. Catalytica was supplied with sub-scale samples of Trap A and Trap B. Details about the vendors and their products are protected under a non-disclosure agreements and are not discussed in this report. The overall conversion for Trap A and B are shown in Figure 3-3 as a function of temperature at a specific space velocity (SV). LNT B was found to be better suited to the expected LNT inlet temperature conditions of 475 to 525° C.

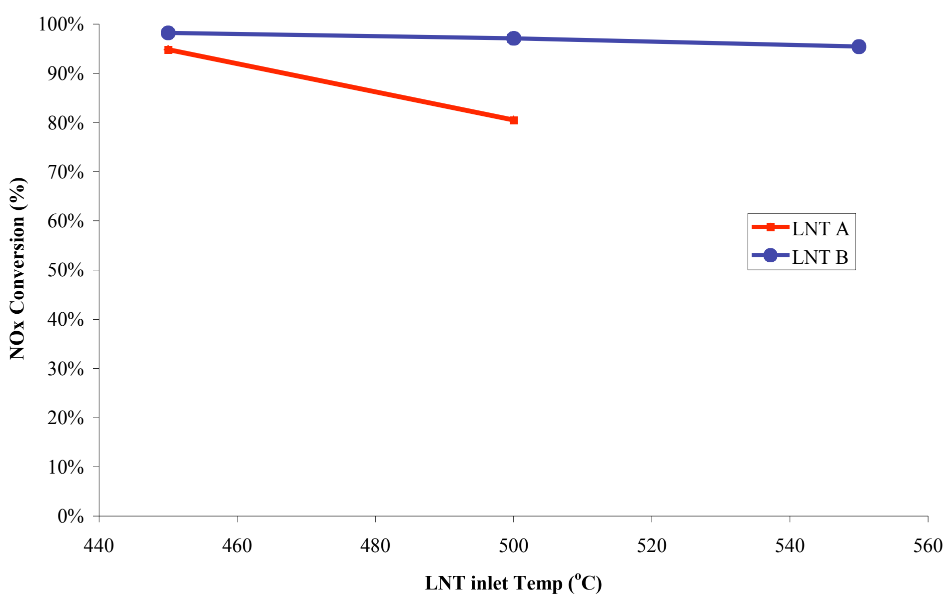


Figure 3-3
NOx Conversion for LNTs A and B as a Function of Temperature, for a Given Space Velocity and Fixed Lean Time

Sub-scale capacity measurements also indicated that LNT B is better suited for full-scale testing. As shown in Figure 3-4, as the trapping time increases (i.e., time period between regeneration cycles), the NOx capture decreases in both traps. However, the capture decreases more rapidly in LNT A than in LNT B. For these reasons, LNT B was selected for the full-scale XEC-90 demonstration unit.

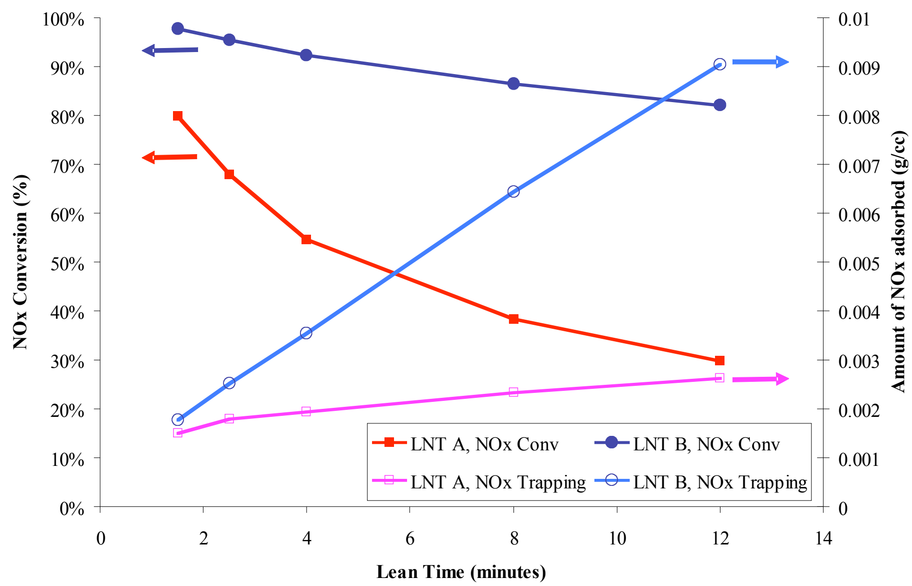


Figure 3-4
NOx Conversion and Capacities for LNTs A and B as a Function of Lean Time, for a Given Space Velocity and Temperature

To predict performance over time, a sample core of LNT B was subjected to steam aging in a test cell which replicated the baseload steady-state operating temperature (without SO_2 so as to decouple the effects of SO_2 and thermal aging on performance). The performance of LNT B was measured periodically at a fixed space velocity and trapping time to determine the sizing and modes of operation for the full-scale XEC-90 test unit. Results from sub-scale tests, shown in Figure 3-5, suggest that for the full scale LNT block size (14 L) supplied by Vendor B, two LNTs (equaling 28 liters of trap volume) would be enough trap material to meet 90%+ NOx conversion for 100 hours (the performance target for this phase of the program). However, in an effort to ensure ample NOx conversion, it was decided to use three LNTs (42 liters of trap volume) for the 8.3 liter Cummins engine demonstration test.

While 42 liters of trap volume for an 8.3 liter displacement engine may seem high (5:1 trap to engine volume ratio) compared to a 2:1 trap to engine volume ratio for mobile engines, it should be noted that, in contrast to the relatively light duty cycle of mobile engines, stationary engines generally operate longer hours close to full load, operating conditions where the NOx production is highest. It should also be noted that the test system was designed as a proof-of-concept system, and as such, it was not optimized for minimum possible LNT volume, something that will be done for commercial XEC-90s. Furthermore, simple interpolation or extrapolation of the 5:1 ratio should not be used to determine the LNT volume for different sized engines. Scaling the trap to engine volume ratio is not straightforward. There is a wide variation in engine specific operating conditions such as NOx concentration, exhaust flow rate, and exhaust gas temperature that can influence this ratio.

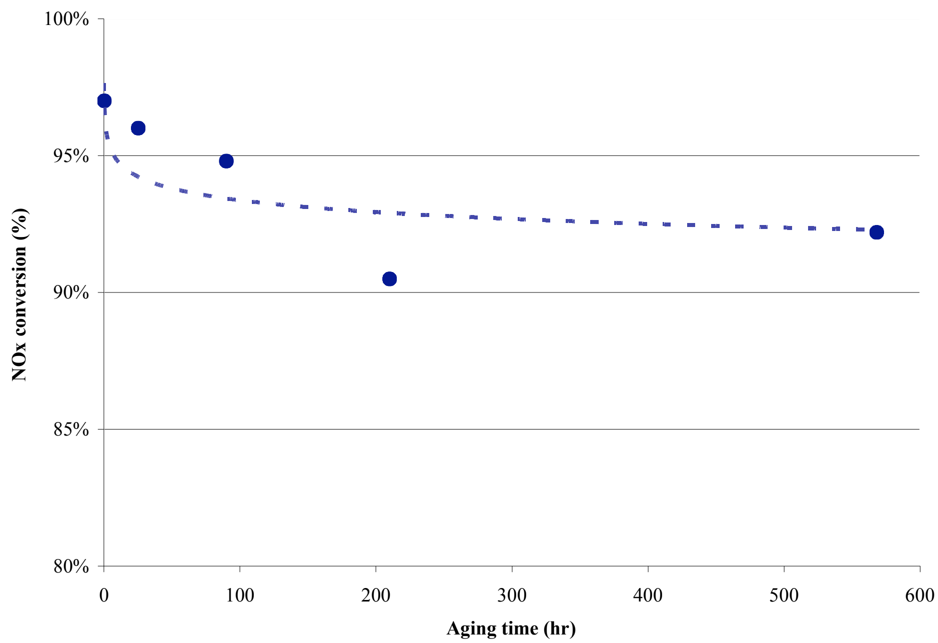


Figure 3-5
NOx Conversion for LNT B as a Function of Steam Aging Time at Baseload Operating Temperature (performance data taken for a given space velocity, temperature and fixed lean time)

Finally, to determine the effect of SO_2 on performance, a sample core of LNT B was subjected to accelerated sub-scale aging for ten hours in the presence of SO_2 levels ten times higher than average actual levels in the exhaust of an engine using ARB ultra low sulfur diesel (15 ppmw sulfur). The results indicated NOx conversion should remain above 90% for the 100-hour demonstration test. Additional long-term sub-scale tests at the expected SO_2 concentration are underway.

Conclusions: These sub-scale results indicate LNT B could meet 90%+ NOx conversion after 100 hours of operation in the presence of 1 ppm SO_2 in the exhaust (assuming 15 ppmw sulfur in the fuel). Results also indicate that two LNT B blocks (28 L) should meet the 90% NOx conversion requirement for 100 hours of operation. However, it was decided to use three LNT blocks (42 L) for the engine demonstration test to provide excess NOx trapping capacity.

Task 4: Engine Testing of the Prototype XEC-90 System

In this task, Catalytica integrated the XFP, lean NOx traps and the test engine together, performed a system shake-down, and conducted the 100-hour demonstration test. During the hardware shakedown, CESI discovered that the actual capacity of the three LNTs was less than had been anticipated from tests of the sub-scale samples. The LNT vendor acknowledged that manufacturing deficiencies in the full-size LNTs might have been responsible for the observed reduction in capacity. This shortfall resulted in inadequate NOx trapping capacity in the full-scale system necessary to maintain 90% NOx reduction for the 100-hour test period. As a result, a fourth trap (56 L total) was added to the system in efforts to meet the performance objectives of the 100-hour test.

Also during the initial XEC-90 hardware shakedown, Catalytica discovered a timing problem with the throttle and XFP fuel flow control. The XFP fuel injection periodically lagged the throttling and the lag time was inconsistent and irregular. This timing issue resulted from a slow accumulation of time delay and did not manifest itself until after extended and continuous operation. This was a minor issue and was addressed with control software changes.

Figure 3-6 is a plot of the NOx conversion versus cumulative operating time between hour 60 and 90 of the 100-hour demonstration test. A limited time window is shown to provide a detailed explanation of the data and operational approach. Each data point represents an average over a period of 1 to 2 hours of data sampled and recorded every second. NOx conversion was derived by measuring NOx concentration at the engine exhaust and XEC-90 outlet using a chemillumensce analyzer. Most of the emissions data were collected at the XEC-90 outlet. Engine exhaust emissions were measured once per hour. Analyzers were calibrated on a daily basis.

The operational approach was targeted at maintaining >90% NOx conversion (based on the 1 to 2 hour average of data recorded every second) by reducing the lean trapping time (i.e., increasing the regeneration frequency) and performing desulfation cycles. For example, between hour 64 and 74, NOx conversion decreased as the traps lost capacity with the accumulation of sulfur. At hour 74, NOx conversion dropped below 90% so the lean trapping time was reduced to offset the loss in capacity. This change increased the NOx conversion back above 94%. By hour 85, the continued accumulation of sulfur reduced NOx trapping capacity, which reduced NOx conversion to 90%. Since the lean trapping time could not be reduced any further, a desulfation cycle was performed. After the desulfation, NOx trapping capacity recovered such that the lean trapping time could be increased while still achieving 94% NOx conversion.

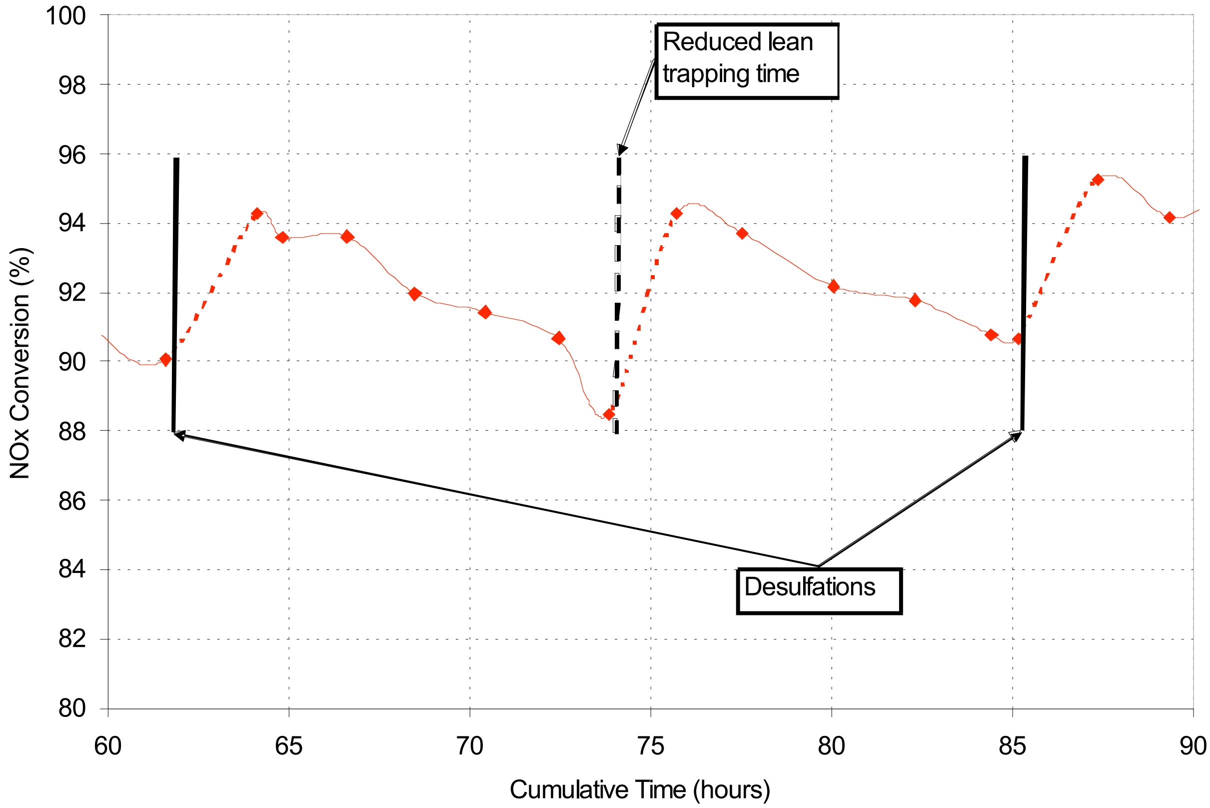


Figure 3-6
Average NOx Conversion Under Steady-state Conditions Versus Operating Time Between Hours 60 and 90, Showing Timing of Desulfation Events

Figure 3-7 is a summary plot of the 106.8 hours of >90% NOx reduction that was demonstrated. Each data point represents a cumulative time weighted average NOx concentration (i.e., the 90.5% NOx conversion at hour 20 is the time weighted average NOx conversion for the first 20 hours of the test; the 91% NOx conversion at hour 40 is the time weighted average NOx conversion for the first 40 hours of the test). The cumulative NOx conversion averaged over the entire 100 hour test was 92%. This NOx reduction effectively lowers the 5.5 g/bhp-hr (16.2 lb/MW-hr) NOx emission certification to 0.44 g/bhp-hr (1.3 lb/MW-hr).

During the first 20 hours of the test, average NOx conversion dropped below the 90% target several times while the control system was tuned and refined. After fine-tuning the control system, the time weighted average NOx conversion remained over 90% and actually increased for the remainder of the test. The cumulative time weighted average NOx conversion increased with time after the first 20 hours because NOx conversion improved to between 90 and 94%, which eventually outweighed the first 20 hours of lower NOx conversion.

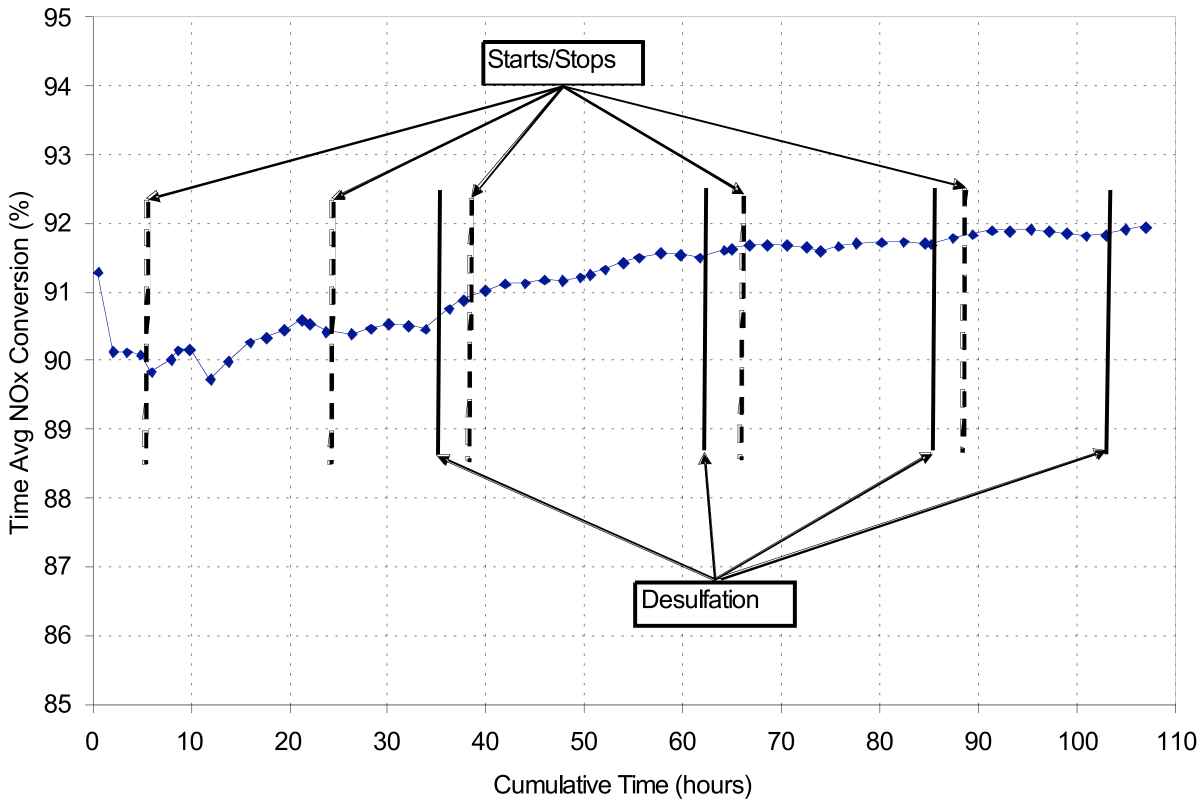


Figure 3-7
Cumulative Average NOx Conversion Under Steady-state Conditions Versus Operating Time with Timing of Desulfation Events

Several engine starts/shutdowns and desulfation cycles occurred during the demonstration test. The five starts/shutdowns were necessary to address engine maintenance issues and computer software data acquisition issues. None of the shut-downs were caused by the XEC-90 catalysts or hardware. NOx conversion typically remained high during a shutdown event because the temperature of the traps remained within the optimal operating range. However, during start-up events, NOx conversion is typically less than 90% as it takes several minutes for the thermal mass of the NOx traps to warm-up to their optimal operating temperature. The lower NOx reduction during start-up has minimal impact on the average NOx conversion since the total time for the five start-ups is less than 0.5 hours of the 100-hour test.

A desulfation was performed when the NOx conversion measured during a one-hour time period dropped below 90%. This operational approach was discussed above in reference to Figure 3-6. A total of four desulfations were performed to maintain the time averaged NOx conversion over 90%.

Fuel penalty is the additional amount of fuel consumed to operate XEC-90 divided by the nominal amount of fuel the engine would have consumed without the added XEC-90 hardware and XFP fuel injection. There are four ways in which fuel use increases (at constant power) when the XEC-90 is in service:

1. The XEC-90 hardware adds back-pressure to the engine. A slight increase in fuel to the diesel injectors is required to maintain constant power out.

2. Engine fuel consumption increases when the intake air is throttled during the LNT regeneration cycle.

   Combining the back-pressure and throttle effect, the *engine* fuel penalty ranged between 2.2 and 2.3%.

3. Diesel fuel is injected into the XFP to produce the H_2 and CO necessary to convert the trapped NOx to N_2 during the regeneration cycle.

   The XFP injector fuel penalty varied between an average of 3.5 and 6% for NOx trap regeneration under steady-state conditions. This variation was due to periodic tuning of the regeneration fueling schedules to maximize NOx reduction.

4. Increased XFP fuel injection is employed during the LNT desulfation cycle.

   The short-term desulfation fuel penalty varied between 13.9% and 23.9% as different fueling schedules were tried. The final desulfation resulted in a short-term 23.9% fuel penalty, but since the desulfations occurred so infrequently, the desulfation fuel penalties had a negligible impact on the average fuel penalty for the 100-hour test.

The average fuel penalty (engine fuel plus XFP injector fuel for all modes of operation) for the entire demonstration test was 7%. It should be noted that the objective in this sub-task was to *measure* fuel penalty, not to optimize it. While undertaking this demonstration test, CESI identified several areas of opportunity to reduce the fuel penalty. These opportunities include (1) a different XFP fueling strategy during regeneration and desulfation to more efficiently utilize the injected fuel; (2) an alternative head-end design to yield a lower pressure drop; and (3) an alternative NOx trap configuration to reduce pressure drop.

4

MARKET AND APPLICATIONS

An XEC-90 commercial product has several market opportunities based on its ability to significantly and inexpensively reduce both NOx and diesel PM emissions. The two primary markets are retrofits for agricultural pumping engines and the conversion of BUGs for peak shaving or demand response duty. Economics of scale savings for production and installation of commercial XEC-90 systems will favor larger engines (~250 to 2,000+ kW), which are typical of these markets – see Figures 4-1, 4-2, and 4-3. Using standby diesel generator set population from public reports[11] for three main regions in the United States (California, Texas and North East States), an estimate of the North American BUG market opportunity can be seen in Figure 4-1 below.

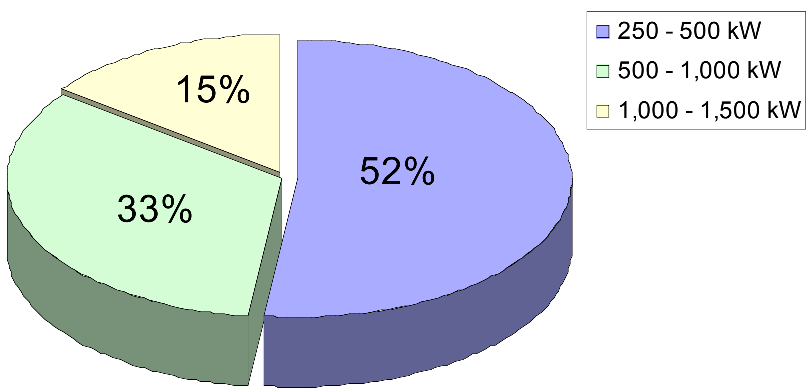


Figure 4-1
North American BUGs Market Opportunity

[11] 1) *Estimates of Emissions for Small Scale Diesel Engines*. Dec 2003. Environ International Inc., 2) *Stationary Diesel Engines in the Northeast*. June 2003 3) *CEC BUGs Inventory Database*. 2001

Figure 4-2 below shows the number of BUGs by region in the 500 kW – 1.0 MW range.

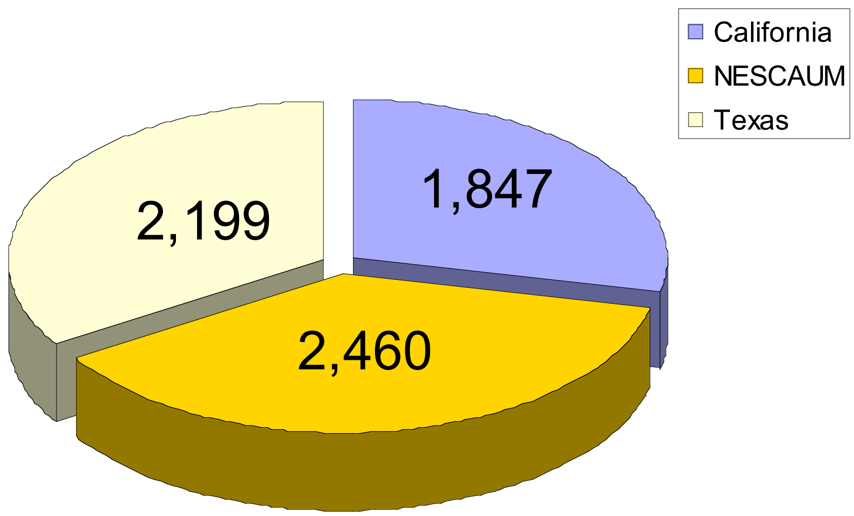


Figure 4-2
500 – 1,000 kW BUG Opportunity by Region

Figure 4-3 below shows the number of BUGs by region in the 1.0 – 1. MW range.

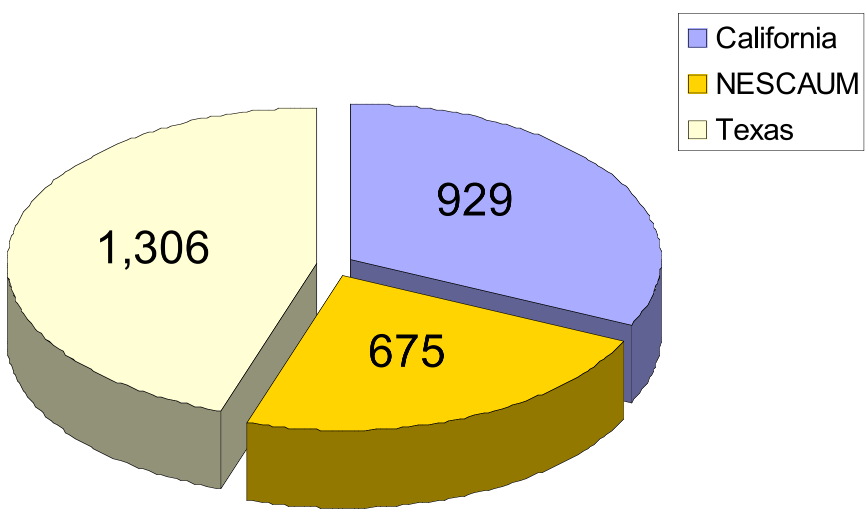


Figure 4-3
1,000 – 1,500 kW BUG Opportunity by Region

Based on these preliminary market data, Catalytica decided to target 500 kW and 1,000 kW sized engines for Phase II. This size range bounds a significant fraction of the available target market. California is an important market for Catalytica since approximately 25% of 500-1,000 kW BUGs and 33% of 1,000-1,500 kW BUGs are located in the state. Even with modest market penetration of a combined NOx and diesel PM product, the benefits to California can be significant.

Rolling Blackout Reduction Programs

BUG owners may also participate in some utilities' rolling blackout reduction programs. These programs, approved by the California Public Utilities Commission, allow utility customers to reduce their electric demand in exchange for credits against their energy bill. The customer load is first surveyed by the utility to establish a baseline. Then, during periods of high demand when grid stability is at risk, the utility may contact the customer and request that they curtail their load. Curtailment can be accomplished through a combination of load reduction and self-generation. Most programs offer $0.20/kW-hr of reduced load, with a 100 kW or 15% minimum demand reduction required to qualify for credit. Engines used for this program will be subject to PM mitigation requirements or face severe limits on hours of operation if they are exempt BUGs. Engines that are retrofitted with XEC-90 and re-permitted for dispatchable service will have greater flexibility for self-generation.

Peak Shaving with Back-Up Generators (BUGs)

In most jurisdictions, emergency generators are exempt from permitting. Their operations are limited to times when grid power is unavailable, and maintenance testing. The XEC-90 with PM control will reduce emissions to a point where engine owners may find it profitable to dispatch their engines for peak shaving during the summer season. Dispatchable diesel power can also help end-users avoid demand charges by reducing their load served from the grid. In California there is over 3,880 MW of installed BUG capacity in units greater than 300 kW. This represents a considerable underutilized potential generation resource if emissions are lowered.

Stationary Agricultural Diesels

Stationary agricultural diesel engines are used mostly for water pumping. There are approximately 5,900 such units in California. These represent a significant swing capacity: work being done by diesels that would otherwise be done with electric motors. The equivalent electric capacity would be at least 1,400 MW, assuming a nominal 250 kW load for each unit. If these pumps were electrified, it would be problematic for California to meet this additional electricity demand during summer afternoons. Furthermore, the cost of bringing in new power lines, capital and construction costs for the new electric motor, and the subsidized cost of electricity to drive the pump, will be passed on to the California consumers in the form of higher cost of electricity and agricultural products.

New ATCM rules require these engines to make large scale reductions in their emissions. Retrofitting with XEC-90 and a certified DPF represent a much simpler and more cost effective solution than re-powering these pumps with electric motors or replacing them with new diesel engines. Considering the high NOx and PM emissions rates of existing agricultural diesels, a 95% NOx reduction and 85% diesel PM reduction represents a much larger tonnage reduction than does a 85% DPF on its own, as required by ATCM – an added benefit of using an XEC-90 product.

Portable Diesel Engine Systems

Portable diesel systems are used for power generation, air/gas compression, pumping, and other mechanical drive applications. According to ARB, there are about 50,000 portable diesel engines in operation in California[12]. Portables are coming under increase scrutiny for all emissions. These units will be required to meet new engine standards for PM emissions by 2010. The XEC-90 (at 95% NOx reduction) with a DPF will meet NOx and PM standards in all California air districts for these systems. Rental and leasing companies, therefore, represent a significant market for retrofits, where local compliance at the customer's location will drive the need for clean, portable power and mechanical drive systems.

Competing Technologies

The XEC-90 program will face competition from other after treatment technologies offering 90%+ NOx reduction. Currently, SCR seems to be the only viable technology that brings NOx reduction in the 90%+ range. There are a number of manufacturers selling these products into the stationary diesel market. Companies currently promoting and selling SCR technology to the diesel power generation market are:

- Johnson-Matthey – SCRT system
- Engelhard – sells the Kaparta SCR system developed by Hug Industries of Switzerland
- Argillona – a spin-off of Siemens that offers the SiNOx SCR system
- Sud-Chemie – German based company that offers SCR, lean NO_x, PM catalysts
- Haldor Topsoe – Danish company offering the DeNOx SCR system

[12] *Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-fueled Engines and Vehicles*. October 2000. California Air Resources Board: Stationary Source Division and Mobile Source Control Division.

Table 4-1
Summary Comparison of SCR and CESI XEC-90

Product	Advantages	Disadvantages
Selective Catalytic Reduction (SCR)	• Proven technology, 90%+ NOx reduction demonstrated • Commercially available • Applicable to many markets • Simple • No associated fuel penalty	• Expensive to install and operate • Large systems • Potential for ammonia slip; control would require an oxidation catalyst
CESI XEC-90	• No urea • Applicable to mechanical and electronic fuel systems • Builds on CESI's XFP fuel reforming competence • Substantially lower cost than SCR systems	• Fuel penalty • Unproven technology

5 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Catalytica successfully completed the four major tasks in Phase I of the XEC-90 development Program. For Task 1, the upgraded LabVIEW control system demonstrated automated throttling. In Task 2, the XEC-90 hardware was designed and fabricated. Several XFP catalyst materials were evaluated and the most suitable was selected. For Task 3, sub-scale evaluation of two different LNTs showed that for LNT B, three blocks should more than meet the 90% NOx conversion requirement for 100 hours of operation. And finally, in Task 4, CESI successfully demonstrated the feasibility of a >90% NOx reduction system for 100 hours on a stationary, 160 kW diesel generator set. The measured average fuel penalty for the entire test was ~7%, but this fuel penalty was not optimized.

The cumulative NOx conversion averaged over the entire 100-hour test was 92%. During the first 20 hours of the test, average NOx conversion dropped below 90% several times while the control system was being tuned and refined. After fine-tuning the control system, NOx conversion remained between 90% and 94% with the cumulative time weighted average NOx conversion increasing with time after the first 20 hours (see Figure 3-7).

During the hardware shakedown exercise, Catalytica discovered that the actual capacity of the full-scale LNTs was significantly less than predicted, based on the sub-scale LNT test results. The LNT vendor suggested that the capacity difference was due to their prototype production process depositing a non-uniform washcoat loading on the full-scale traps. The vendor explained that this performance shortfall would not be expected from commercially manufactured traps where the appropriate process and quality controls are in place. The NOx trapping capacity shortfall resulted in the inability of the prototype hardware to maintain 90% NOx reduction for an extended period of time. As a result, a forth trap (56 L total) had to be added to the system to meet the performance objectives of the 100-hour test. Subsequent sub-scale tests of samples from the full-sized LNTs confirmed the difference in performance of the full-sized versus sub-scale sample LNTs. Improved LNT manufacturing procedures would have enabled the tests to be successfully performed with three traps (42 L total), as predicted in Task 3.

During the hardware shakedown execution of Task 4, CESI discovered a timing problem with the throttle and fuel control logic that was the result of a slow accumulation of time delay. This was corrected with software changes.

Recommendations

The technical performance achieved during Phase I (and the potential for continued performance improvements) and the anticipated market demand, recommend continuing product development and field trials, proposed as Phase II. Phase II development and field trials will include:

- Integrate the XEC-90 with an ARB-certified diesel particulate filter and produce two integrated units for field trials with design goals of 95% NOx and 85% DPM removal at minimal fuel penalty. One unit will be sized for a 500 kW engine and the second for a 1,000 kW engine.
- Install these two units on existing diesel engines at two different locations and operated for 1,000 hours each under normal operating conditions.

At the completion of the Phase II field demonstration the results will be analyzed and a decision made as to whether to proceed with Phase III, wherein the XEC-90 product will be made available to the general public on a limited release basis while the pilot manufacturing details are worked out and preparations made for a full commercial release.